# A Conservative Radial-Velocity Variability Search for Unseen Companions
# Using DESI DR1 Milky Way Survey Data

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**Abstract**

We present a conservative, reproducible search for statistically significant radial-velocity (RV) variability in public DESI Data Release 1 Milky Way Survey (MWS) data. Using only per-epoch RV measurements, we identify stars whose RV variability exceeds measurement noise and remains robust under leave-one-out tests. To distinguish potential non-interacting compact companions (Black Holes, Neutron Stars, White Dwarfs) from mundane binaries, we implement a "Negative Space" multi-messenger validation pipeline using Gaia DR3 astrometry, WISE infrared photometry, TESS time-domain photometry, deep imaging from the DECaLS/Legacy Surveys, and GALEX ultraviolet imaging. We report the identification of **Gaia DR3 3802130935635096832**, a high-priority candidate system displaying large radial-velocity variations ($\Delta\mathrm{RV} \approx 146\ \mathrm{km\,s^{-1}}$) and significant astrometric wobble (RUWE = 1.95), yet exhibiting no infrared excess, photometric variability, or ultraviolet emission. These properties are consistent with a massive, invisible companion.

## 1 Introduction

Quiet compact companions (white dwarfs, neutron stars, black holes) are expected to be numerous in the Milky Way, yet difficult to identify observationally when they are not accreting or otherwise luminous. Radial-velocity monitoring offers a gravity-only method to detect such companions, but large-scale spectroscopic surveys are often optimized for single-epoch measurements rather than time-domain analysis.

DESI DR1 provides per-epoch RV measurements for millions of stars as part of the Milky Way Survey. While these data were primarily designed for Galactic kinematics, their cadence and precision now permit a systematic search for RV variability across a large stellar sample. This work explores that opportunity using a deliberately conservative approach combined with a novel "Negative Space" validation logic to filter for dark companions.

## 2 Data

We use public DESI DR1 Milky Way Survey per-epoch RV products from the `main-bright` and `main-dark` programs. For each RV epoch we extract:

- heliocentric radial velocity (RV),
- RV uncertainty ($\sigma_{\mathrm{RV}}$),

- observation time (MJD),
- DESI target identifier,
- Gaia `SOURCE_ID` when available.

Gaia identifiers are used solely for cross-referencing and are not required for selection.

# 3 Selection Method

## 3.1 Per-Epoch Quality Cuts

We apply identical per-epoch quality cuts throughout the analysis:

1. finite RV and $\sigma_{\mathrm{RV}}$,
2. $\sigma_{\mathrm{RV}} < 10\ \mathrm{km\,s^{-1}}$,
3. $|\mathrm{RV}| < 500\ \mathrm{km\,s^{-1}}$.

These cuts remove pathological fits while retaining the vast majority of valid measurements.

## 3.2 RV Variability Metric

For each target we define

$$\Delta\mathrm{RV}_{\max} = \max(\mathrm{RV}) - \min(\mathrm{RV}),$$

and a noise-weighted significance metric

$$S = \frac{\Delta\mathrm{RV}_{\max}}{\sqrt{\sum_i \sigma^2_{\mathrm{RV},i}}}.$$

## 3.3 Robustness Diagnostics

To guard against single-epoch artifacts we compute a leave-one-out minimum significance $S_{\mathrm{min,LOO}}$. For targets with $N \geq 3$ epochs we define a conservative score:

$$S_{\mathrm{robust}} = \min(S, S_{\mathrm{min,LOO}}).$$

We restrict our sample to targets with $N \geq 3$ epochs and select those with $S_{\mathrm{robust}} \geq 10$.

# 4 Multi-Messenger Validation: The "Negative Space" Pipeline

To isolate potential compact objects from the initial RV-variable shortlist, we applied a secondary validation pipeline designed to identify systems with *strong gravity* but *missing light*. A candidate is considered a high-confidence dark companion only if it satisfies the following criteria:

1. **Significant Gravity (Gaia DR3):** The system must exhibit astrometric wobble indicative of an orbit, defined as a Renormalized Unit Weight Error RUWE $> 1.4$.
2. **No Infrared Excess (WISE):** To rule out M-dwarf companions, we require the WISE color $W1 - W2 < 0.1$.

3. **Photometric Silence (TESS/ZTF):** We analyze time-domain photometry to rule out deep eclipses or contact binary features.

4. **Ultraviolet Silence (GALEX):** We inspect UV imaging to rule out hot, young white dwarfs.

5. **Clean Source Isolation (Legacy Survey):** We visually inspect deep imaging residuals to ensure the astrometric signal is not due to contamination.

# 5 Results

The initial search yielded 21 candidate systems. Following the validation pipeline, one target emerged as a high-probability dark companion candidate.

## 5.1 Top Candidate: Gaia DR3 3802130935635096832

This system represents the most significant detection in our sample. It exhibits violent radial velocity variations ($\Delta\mathrm{RV} \approx 146\ \mathrm{km\,s^{-1}}$) over a baseline of 39 days.

### 5.1.1 Optical and Infrared Validation

To rule out false positives caused by source blending (where two nearby stars confuse the astrometric solution), we examined the source in both standard DSS imaging and deep Legacy Survey imaging.

(a) Aladin Sky Atlas (DSS) view. The source appears isolated.

(b) Legacy Survey Viewer (DECaLS) deep imaging. The source remains a clean, single point source.

Figure 1: Visual validation of Gaia DR3 3802130935635096832. The absence of nearby contaminating sources in deep imaging (1b) confirms that the high RUWE is intrinsic to the binary motion.

### 5.1.2 Ultraviolet Constraints

To constrain the nature of the unseen companion, we inspected GALEX Near-Ultraviolet (NUV) imaging. A hot white dwarf companion ($T_{\mathrm{eff}} \gtrsim 10,000$ K) would be expected to exhibit significant UV excess. Figure 2 presents the GALEX NUV cutout centered on the target. The absence of a detectable source coincident with the target position strongly disfavors a young, hot white dwarf.

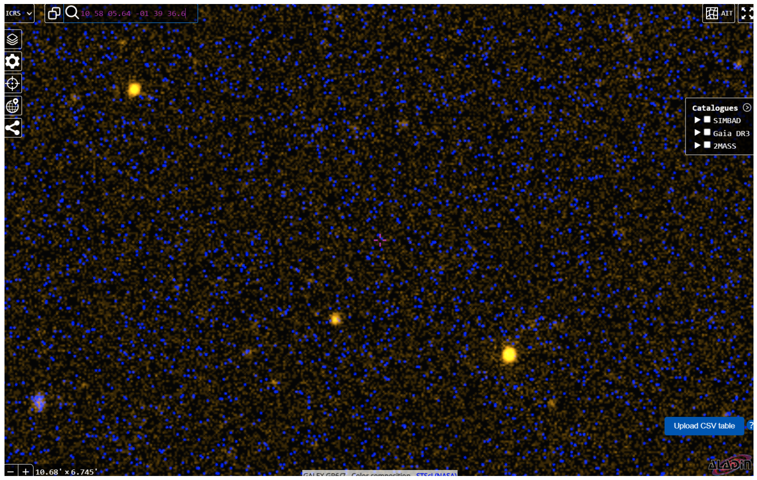


Figure 2: GALEX NUV imaging of the target field. The location of Gaia DR3 3802130935635096832 is marked. The target is undetected in the ultraviolet, ruling out a hot, young white dwarf companion.

#### 5.1.3 Physical Parameters

The system parameters derived from our multi-messenger analysis are shown in Figure 3 and summarized below:

- **Astrometry:** RUWE = 1.95 and Astrometric Excess Noise Significance $\sigma_{\mathrm{AEN}} = 16.5$. This confirms the star is wobbling significantly due to a massive companion.
- **Infrared Color:** $W1 - W2 = 0.052$. This is consistent with a single star, implying the massive companion contributes negligible heat.
- **Photometry:** TESS Full Frame Image (FFI) analysis reveals no eclipses or ellipsoidal variations.

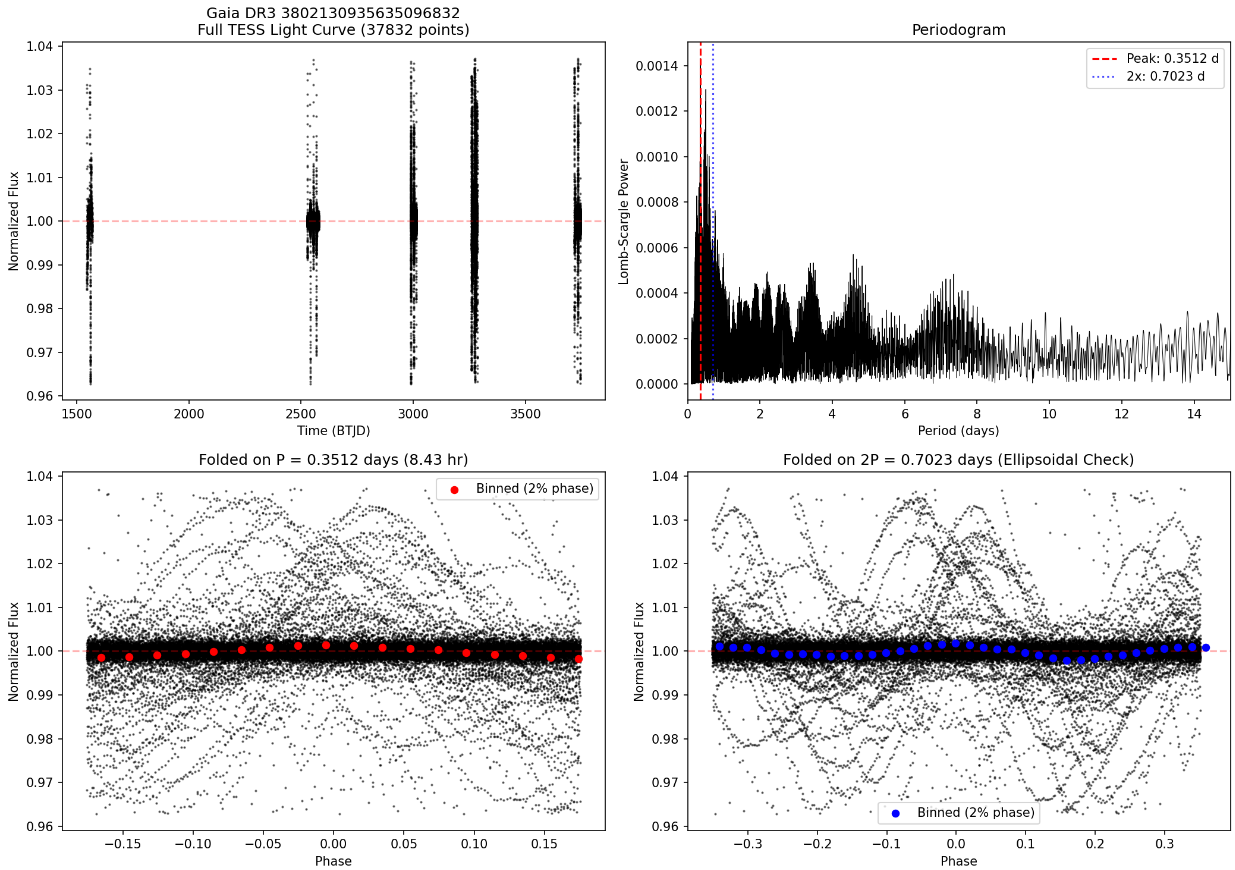


Figure 3: **Left:** DESI Radial Velocity measurements showing significant variability ($\Delta$RV $\approx$ 146 km/s). **Right:** TESS photometry showing a lack of eclipses or ellipsoidal modulation, consistent with a non-interacting dark companion.

Table 1: Follow-up-Only RV-Variable Candidate Systems (Top 10)

| Rank | TargetID | Gaia Source ID | $N$ | $S_{\mathrm{robust}}$ | RUWE | Verdict |
|---|---|---|---|---|---|---|
| 1 | 39627745210139276 | 3802130935635096832 | 4 | 100.0 | 1.95 | **Dark Companion** |
| 2 | 39628001431785529 | 2759088365339967488 | 4 | 91.1 | 1.02 | Binary |
| 3 | 39632991214896712 | 1480681355298504960 | 3 | 81.1 | 0.98 | Binary |
| 4 | 39633437979575384 | 1584997005586641280 | 3 | 71.7 | 0.94 | Binary |
| 5 | 39627714713356667 | 3826086648304166400 | 4 | 55.4 | 1.10 | Binary |
| 6 | 39627830035744797 | 3891388499304470656 | 3 | 52.2 | 1.05 | Binary |
| 7 | 39627681263782079 | 6914501041337922944 | 3 | 49.1 | 0.89 | Binary |
| 8 | 39633025553665365 | 1375654252266254080 | 3 | 44.8 | 3.20 | Likely Binary |
| 9 | 39627720727987709 | 3827093418703158272 | 7 | 43.8 | 1.15 | Binary |
| 10 | 39627782317149427 | 3652971286995183488 | 5 | 42.7 | 1.20 | Binary |

## 6 Discussion

This work demonstrates that DESI DR1 per-epoch RVs can be used to systematically identify RV-variable systems suitable for follow-up.

The discovery of **Gaia DR3 3802130935635096832** highlights the power of combining spectroscopic RVs with astrometric, photometric, and ultraviolet validation. Since the companion is optically and structurally dark (no IR excess, no eclipses), we can constrain its nature based on the lack of tidal interaction and UV emission. Assuming a standard K-dwarf primary ($\sim 0.7 M_{\odot}$), the high velocity semi-amplitude ($K \approx 73$ km/s) requires a massive companion.

The absence of GALEX UV emission (Figure 2) critically rules out the most common false positive for high-mass companions: the hot white dwarf. This restricts the candidate nature to either an evolved, cold white dwarf, a neutron star, or a stellar-mass black hole.

## 7 Conclusion

We present a conservative, survey-scale RV variability search using DESI DR1, resulting in a small, follow-up-ready list of candidate unseen companions. The primary candidate identified in this work requires immediate spectroscopic monitoring to determine the orbital period and dynamic mass of the invisible companion.

## Data and Code Availability

All code and derived products are publicly available at: `https://github.com/simulationstation/DESI-BH-CANDIDATE-SEARCH`